Brain Oscillations and Cognitive Processes

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Brain Oscillations and Cognitive Processes

Description of Group:

Project description

Research plan 1.1. 2004 - 31.12. 2006

1. The aims and goals of the project for 2004-2006

The aim of the present truly multidisciplinary project is two-fold. First, the aim is to collect data on and evidence for the role of brain oscillations in association with human cognitive processes. Second, on a more theoretical level, we aim at increasing knowledge on how brain oscillations make human cognitive processes possible.

Human cognitive processes and information integration will be assessed by means of several experiments. Emphasis will also be put on the development of new EEG-signal analysis and statistical evaluation tools. On the theoretical level, the aim is to associate the empirical findings with current brain oscillatory theories on human information processing. The detailed aims of this project will be described in section 3.

2. Background: how this project is associated with previous scientific activity of the researcher/s

Cognitive neuroscience now leaves little or no doubt that cognitive processes require the transient integration of numerous, widely distributed, constantly interacting areas of the brain. The most plausible mechanism for such a large-scale integration is the formation of dynamic links mediated by synchrony over multiple frequency bands [1]. Neurons can exhibit a wide range of oscillations (theta to gamma-band oscillations ~4-70 Hz) and these oscillations can enter into precise synchrony over a limited period of time (millisecond scale). Recently, the role of brain oscillations in human information processing has been intensively investigated [2-5]. Brain oscillatory systems have been proposed to act as possible communication networks with functional relations to memory and integrative functions [6]. At present, brain oscillations at different frequencies, able to provide both temporal and spatial codes, are one of the most promising candidate mechanisms explaining the neural basis for higher-level information processing.

EEG (and MEG signals arising from the brain consist of several simultaneous oscillations, which have traditionally been subdivided into frequency bands such as delta (1-3 Hz), theta (4-8 Hz), alpha (8-12 Hz), beta (about 14-30 Hz) and gamma (around 40 Hz) (Figure 1).

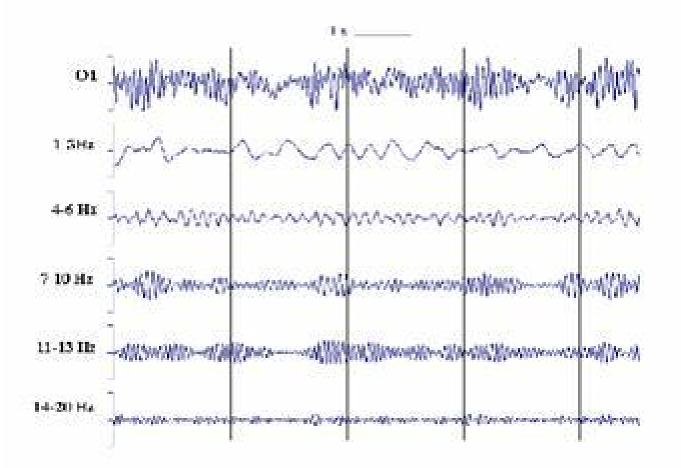

Figure 1. Examples of simultaneously occurring brain electric oscillations digitally filtered from the ongoing EEG (first row) from electrode O1. The y- axis depicts amplitude and the x-axis stands for time. Note that the different frequencies are modulated differently as a function of time in relation to stimulus presentation points (vertical lines).

Different neural generators have been suggested to be involved in the generation of brain oscillations at different frequencies [7]. Hippocampal neural activity seems to be reflected as oscillations within the theta frequency range (~4-8 Hz) [5, 8, 9] while the alpha rhythms (~8-12 Hz) seem to be mainly generated by cortico-cortical and thalamocortical neural networks [5, 10]. The posterior alpha rhythm (~7-13 Hz) typically occurs in the posterior and occipital areas being strongest during relaxation while the tau rhythm (~8-10 Hz) is observed close to the auditory cortices [11, 12]. The beta rhythm (~20 Hz) is generated mainly in the motor cortices [11]. Brain oscillations around 40 Hz (gamma band) have been observed in association with visual, auditory and motor tasks [3, 13-17] and might exist in a number of brain structures with somewhat different functional/behavioral correlates [18].

On the functional level, working memory-processes seem to be reflected as oscillations within the EEG theta frequencies (~4-8 Hz) [5, 19, 20]. The existence of three alpha rhythms in association with cognitive processes has recently been reported: the lower-1 alpha (oscillations around 6-8 Hz) which responds to cognitive processes characterized as “alertness”, the lower-2 alpha (oscillations around 8-10 Hz) which is modulated as a function of attentional demands [21], and the upper alpha (oscillations around 10-12 Hz), modulated mainly by stimulus-related aspects and/or semantic memory processes [9, 22-24]. The beta rhythm (~20 Hz) is usually desynchronized during motor tasks and synchronized (beta rhythm rebound) shortly after movement [25] and reflects the activity of the motor cortices [11, 26-28]. Beta rhythm responses have been observed also during observation of other´s movements and during motor imagery. In studies using various tasks, separate foci of simultaneously occurring oscillations around 40 Hz in cortical regions, have been reported. High-frequency brain oscillations may be related to the rapid binding of sensory information in different brain areas [3, 13].

Many kinds of events can induce time-locked changes in the activity of neuronal populations. Psychophysiological EEG and MEG research on time-locked cortical correlates of information processing has mainly focused on the so-called evoked responses (ERs). However, the ERs can be considered as resulting from the reorganization of the phases of brain oscillatory activity. There exist two frequency- specific changes/responses in the EEG/MEG signal: synchronization (power increase) and desynchronization (power decrease). Synchronization (i.e., enhancement in amplitude) can be either evoked (both time- and phase-locked to a given stimulus or event) or induced (time- but not phase-locked to the stimulus or event) [29-32]. In induced oscillatory

activity, both the latency and phase exhibit jitter from trial to trial, the temporal relationship with stimulus onset being relatively loose [15]. Induced activity is usually not revealed by traditional averaging techniques [31, 32].

Event-related brain oscillatory responses can be quantified by means of the so-called ERD/ERS (event-related desynchronization/synchronization) technique: ERD is defined as the event-related individual relative decrease and ERS is the relative increase in the power of a specific frequency band [33]. The ERD/ERS responses of different frequencies within the EEG/MEG are functionally distinct. For example, during auditory memory encoding alpha (10-12 Hz) power typically increases whereas alpha suppression is observed during memory retrieval [34-37]. In contrast, theta (4-6 Hz) synchronizes during memory encoding and becomes even more synchronized during memory retrieval [37]. The temporal differences between the ERD/ERS responses of different frequency bands are of relevance. Theta ERS is usually observed at 100-300 ms, alpha ERD is observed at 500-1500 ms after stimulus onset, 18-20 Hz power changes can be observed at 1000 ms prior to movement onset while brief evoked gamma band responses peak at 100 ms after visual stimulus onset [38]. Brain oscillations may be capable of providing the temporal framework within which information is organized and transferred in the human brain. Time, and the temporal integration of information are undoubtedly among the most important properties of human cognition. Theoretically, alpha, theta, and beta oscillations are too slow to serve as carrier signals for cognitive processes (e.g., “online” speech perception), whereas oscillations at higher frequencies are physically appropriate to establish a rapid coupling of spatially separate cell assemblies [39]. On the basis of previous research [4, 5, 16, 36, 39, 40], it may be hypothesized that theta and alpha oscillatory networks most probably are involved in long-term information encoding and retrieval, whereas brain oscillations at higher frequencies (> 20 Hz) participate in the rapid co-ordination of multiple brain processes during information encoding and integration. Due to recent advances in signal-analysis techniques (e.g., wavelet analyses), it is now possible to examine the simultaneously occurring time-locked responses of the brain’s oscillatory activity at different frequencies by means of Time-Frequency-Representations (TFRs) (Figure 2).

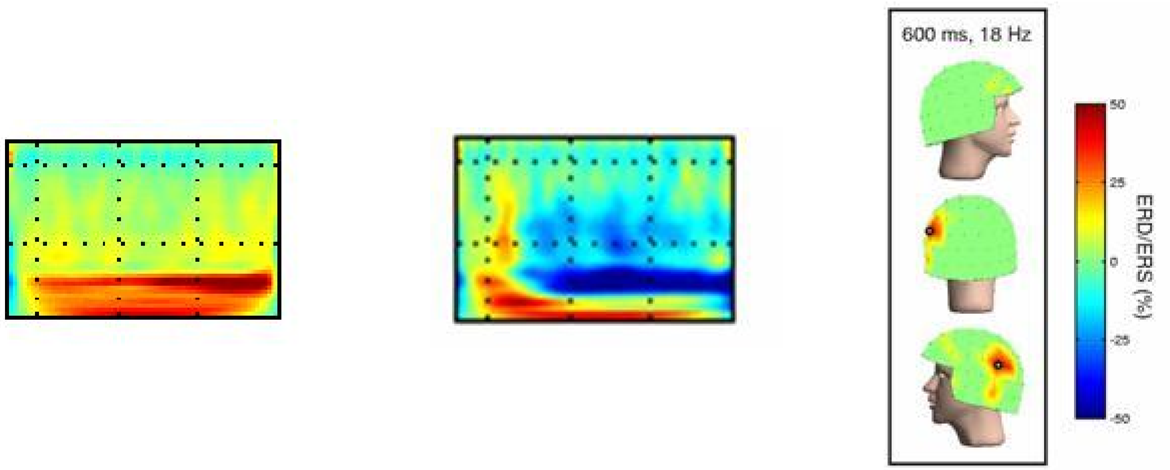

Figure 2. Left: Time Frequency Representations (ERD/ERS TFRs) of EEG data obtained from an auditory memory task. Different frequencies (1-45 Hz) are depicted in the y-axis. Time is illustrated in the x-axis (-200-1600 ms after stimulus onset). “Hot” colors indicate increase in amplitude (ERS) whereas “cold” colors denote decrease in amplitude (ERD). Memory encoding (upper left figure) elicits an increase in amplitude at ~7-18 Hz at 1000-1500 ms after auditory stimulus (word) onset. In contrast, retrieval from memory (lower left figure) is accompanied by an amplitude decrease at ~7-10 Hz at 1000-1200 ms after auditory stimulus (word) onset.

Retrieval from memory evokes additionally power increases in the higher frequencies (15-40 Hz) peaking at ~600-800 ms after stimulus onset. The TFRs obtained during auditory memory encoding and retrieval illustrates the complicated structure of brain electric oscillatory responses at different frequencies during auditory memory processes. Right: An example of a topographical map of of TFR data.

TFRs display the variations in power of multiple frequency bands, as a function of time. The TFRs obtained from different EEG/MEG recording sites can be compared with each other in order to get an estimate of their topographic variation. By means of such multifold analyses, it is possible to assess at which frequencies, and where in the brain a specific oscillatory response occurs, as a function of experimental task.

Currently, there still exist several paradoxes in cognitive neuroscience: First, the anatomy of the human brain is well known but the mechanisms of how this organ processes information are not yet understood. Second, there exists a methodological dualism in current cognitive neuroscience between studies focusing on localization vs. those focusing on the temporal aspects of cognitive processes. Throughout the current study, the theoretical framework is that brain oscillations, at infinite frequencies, in infinite time and sources may be capable of providing the temporospatial framework within which information is organized, stored and transferred in the human brain and further that brain oscillations are of fundamental importance for mediating and distributing such “higher-level” processes [2, 5, 39].

Krause and colleagues were the first to examine and to report of auditorily elicited brain oscillatory (ERD/ERS) responses in association with cognitive and memory processes. Funding is needed to continue this avenue of research in Finland.

3. Practicalities: Schedule, state of art, yearly workplans, individual contributions

The present project will be carried out at Department of Psychology at the University of Helsinki where all necessary laboratories and computational resources exist. The details are described below.

3.1. Differences between auditory vs. visual cognitive processing systems

The aim is to assess differences/similarities in information storage and retrieval systems in the two modalities by means of cross-modal EEG experiments. We will try to answer the following questions: Which brain oscillatory responses at which frequencies during cognitive processes are modality-specific and which are not? Are there any brain oscillatory frequencies, which specifically respond to the task executed, regardless of stimulation modality? The temporal structure of information provided by the visual and auditory systems differ from each other, but how are such temporal variations encoded in the human brain? Oscillations in the theta and alpha frequencies are assumed to be able to mediate long-term information encoding and retrieval processes of both auditory and visual information but the integration of temporal information must occur at other, higher, e.g., the beta (~20 Hz) or gamma band frequencies (~40 Hz).

3.2. Integration of natural speech information

Speaking and understanding speech are results of complex, rapid integration processes in the

human brain, involving visual, auditory and also motor cortical networks. The neural mechanisms underlying the process through which a thought becomes understandable speech, and how we understand speech, are still largely a matter of debate. Successful communication through speech requires a rapid and accurate simultaneous production and analysis of auditory and visual information. The EEG signal has an excellent temporal resolution and is thus appropriate for investigating the temporal aspects of speech perception. In theory, brain oscillations are able equally to provide the temporal and spatial codes needed for successful speech perception/production. We hypothesize that brain oscillations mediate the fast information integration necessary during natural, i.e., audiovisual speech perception. Krause et al. [42] have already reported specific alpha responses (8-12 Hz) during auditory speech perception: In the present study, simultaneous brain oscillatory responses at multiple frequencies (1-45 Hz) will be assessed during natural speech perception (seeing the speaker). One initial study by Krause et al. [43] reported that the perception of audiovisual utterances evoked brain oscillatory responses not only in the alpha (~10 Hz) but also in the beta (~20 Hz) frequency range, the latter suggesting that also the motor cortices, too, became activated during audiovisual information perception. The aim is to reveal compound brain oscillatory networks mediating natural speech perception.

3.3. Effects of stimulus modality on memory processes

Memory encoding and retrieval are two distinct processes in the human brain, which can also be seen as differences in the brain oscillatory responses evoked by these two mental processes. However, identical auditory and visual memory tasks typically elicit divergent alpha responses, which must be considered as at least partially modality-specific responses. This part of the project will examine how these two mental processes differ depending on the input modality, i.e., are there modality specific and/or modality unspecific brain oscillations involved in the cognitive processing (encoding and retrieval) of information presented in different modalities. Most of the prior work on brain oscillatory responses during memory processes has been conducted unimodally and by examining only a few frequency bands, whereas in the present study the responses of several frequency bands (1-45 Hz) will be examined. If applicable, this study will also advance to experimentally assess brain electric oscillations while “something goes wrong”, i.e., when information is not efficiently stored or cannot be correctly retrieved (experimentally manipulated), which can be assessed by means of single-trial analyses of the EEG signal.

3.4. Effects of memory load and other factors on memory processes

The term working memory refers to a system, which is involved in the transient storage and manipulation of information that is needed during the performance of cognitive tasks. In general, an increase in memory load as well as in task difficulty alters brain oscillatory activity especially in the theta (4-6 Hz) and alpha frequency ranges (~8-12 Hz) [44]. There also exist other, both external and internal factors, which affect memory/task performance. How do such “distractors” (e.g., stress, emotional content of the stimuli, stimulus type) affect attention and memory-related processes at the neural level? Are there any differences between the auditory and visual stimulus modalities (storage, retrieval, access to stored information)? Such issues will be examined experimentally by investigating brain oscillatory activity by means of the EEG. The purpose is to try to clarify how various external and internal factors (e.g., information overload, multiple tasks, attention, stress etc.) affect cognitive processes and performance at the neural level. A better understanding of such mechanisms leads to a better understanding of possible facilitators and distracters of cognitive processing.

3.5. Learning, forgetting and memories

The neural mechanisms underlying long-term memories are unknown. Brain electric oscillations at 4-12 Hz (theta and alpha) have been proposed to play a central role in mediating not only cognitive but also memory processes. The purpose of this section is to gain new insights into the possible relationships between brain electric oscillations, memories, learning, and forgetting. For this purpose, memory tasks will be designed which will involve both short- and long-term memory processes. Short-term memory processes may be mediated by means of brain oscillations at the theta frequencies whereas long-term memory processes most probably are mediated via oscillations at other frequencies (alpha and beta), depending on the material and modality in which information is presented. The aim is to distinguish between the neural systems underlying visual and auditory STM and LTM processes, and to determine how visual and auditory information are integrated and affect each other during memory processes.

3.6. Interindividual variation in the EEG: its causes and consequences

The data gathered from the experiments will be individually analyzed. The EEG-responses are characterized by a great inter-individual variation which at present is without any explanation. The aim of this part of the study is to assess some of the causes for this variability. The mean EEG responses rarely reflect the responses of the entire population studied. The central questions of this part of the study are as follows: 1. What causes this variability between subjects (is it possible to assess)? 2. What are the consequences for the (mean) results from the studies? 3. How to take this existing inter-individual variability into brain oscillatory models on human cognition - instead of just ignoring it?

3.7. Trial-to-trial variation in the EEG: its causes and consequences

Brain oscillatory responses are not identical from single stimulus presentation to another. The reason for this variability is unknown. This variability is lost with typical averaging techniques. The variability in brain oscillatory responses may not be due merely to “random noise” in the brain electric signal but reflect the variability in the state of the brain. Single-trial analyses will be performed on the data from the above mentioned experiments when appropriate in order to assess the most typical and probable brain oscillatory responses to cognitive tasks (instead of the largest, as revealed by means of traditional averaging procedures).

3.8. Theoretical issues – the role of brain electric oscillations in cognitive processing

This project will result in a great amount of experimental data, which can be utilized in several theoretical papers. When all empirical facts obtained from the experiments are but together, we will be able to contribute to the discussion on how brain oscillatory networks integrate and mediate human cognitive processes. The aim is to contribute to the theoretical discussion on brain oscillatory models on human cognitive processes.

3.9. Methods

Recent technical and computational advances allow for increasingly sophisticated approaches

on the EEG signal. One of these approaches is the so-called Time-Frequency Representation (TFR) of the EEG signal, by means of which it is possible to estimate the simultaneous event-related responses of multiple frequency bands. Thus it is possible to illuminate the complexity of brain oscillations in association with cognitive processes. Besides the TFR analyses of the EEG signal, we will also be able to examine the phase-locking of the synchronization responses of different brain oscillatory frequencies, and thus to separate induced and evoked oscillatory activity from each other (which otherwise cannot be distinguished from each other). By means of single-trial analyses of the EEG signal, we will be able to assess the degree of stability vs. non-stationarity of these signals in response to stimulation [41]. Thus, we will be able to assess the event-related degree of variability in the EEG signal in addition to traditional comparisons of mean responses. Finally, individual variations in these responses will be examined.

When the differences between the stimuli and/or experimental tasks become small and hard to distinguish (e.g., single words, encoding and retrieval of these), it may not be possible to assess the evoked differences in brain electric activity by means of averaging or by means of traditional statistical tools. Therefore, approaches enabling 0ne to extract subtle but separate components from the EEG signal (reflecting separate aspects of information processing) are necessary in order to reveal the neural correlates of cognitive processes. All psychophysiological experiments in the present study will logically be accompanied by behavioral experiments in which, e.g., task performance and stimulus qualities will be independently assessed.

4. Results, publications and the relevance of the results

The present project aims at shedding light on the neural basis underlying human information processing by examining brain oscillations. At present, brain oscillations are one of the most prominent candidates for explaining both the temporal and spatial aspects of human cognitive capacities. The results from the present study will undoubtedly give new insights into the oscillatory mechanisms underlying human information processing. We aim at illuminating the complex interplay between brain oscillations at different frequencies, able to provide the necessary temporal and spatial codes for human information storage and retrieval. The results will be of international interest and will add to theories on the functional role of brain oscillations in association with human cognitive functioning.

Theories on brain oscillations still need additional experimental validation. We aim at improving these theories on the neural mechanisms underlying human information processing. We will be able to gather high-quality EEG data, and with high- quality signal analysis tools, we will be able to contribute to the further elaboration of these theories. The new and more powerful brain signal analysis tools, which will be developed in this project, will also be of interest at the international level. The more we learn about how the human brain processes, stores and retrieves information, the better we will be able to understand factors which facilitate effective learning, information retrieval and information integration, i.e., capacities which will play an increasingly important role in the society in the future. Basic research on normal brain functioning also gives us tools to study various states of “altered information processing” (e.g., Alzheimer’s disease, schizophrenia and Parkinson’s disease).

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